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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

IN RE APPLICATION OF: Andrew J. SHIELDS, et al. GAU:

SERIAL NO: 09/713,242 EXAMINER:

FILED: November 16, 2000

FOR: A PHOTON SOURCE

REQUEST FOR PRIORITY

ASSISTANT COMMISSIONER FOR PATENTS
WASHINGTON, D.C. 20231

SIR:

☐ Full benefit of the filing date of U.S. Application Serial Number [US App No], filed [US App Dt], is claimed pursuant to the provisions of **35 U.S.C. §120**.

☐ Full benefit of the filing date of U.S. Provisional Application Serial Number , filed , is claimed pursuant to the provisions of **35 U.S.C. §119(e)**.

■ Applicants claim any right to priority from any earlier filed applications to which they may be entitled pursuant to the provisions of **35 U.S.C. §119**, as noted below.

In the matter of the above-identified application for patent, notice is hereby given that the applicants claim as priority:

COUNTRY	APPLICATION NUMBER	MONTH/DAY/YEAR
UNITED KINGDOM	9927107.4	November 17,1999
UNITED KINGDOM	9927690.9	November 23, 1999

Certified copies of the corresponding Convention Application(s)

■ are submitted herewith

☐ will be submitted prior to payment of the Final Fee

☐ were filed in prior application Serial No. filed

☐ were submitted to the International Bureau in PCT Application Number .
Receipt of the certified copies by the International Bureau in a timely manner under PCT Rule 17.1(a) has been acknowledged as evidenced by the attached PCT/IB/304.

☐ (A) Application Serial No.(s) were filed in prior application Serial No. filed ; and

(B) Application Serial No.(s)

☐ are submitted herewith

☐ will be submitted prior to payment of the Final Fee

Respectfully Submitted,

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The Patent Office

Request for grant of a Patent

Form 1/77

Patents Act 1977

❶ Title of invention

1 Please give the title of the invention: A Photon Source.

❷ Applicant's details

❑ **First or only applicant**

2a If you are applying as a corporate body please give:

Corporate name: Toshiba Research Europe Limited

Country *(and State of incorporation, if appropriate)*: UK.

2b If you are applying as an individual or one of a partnership please give in full:

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2c **In all cases**, please give the following details:

Address:
Cambridge Research Laboratory,
260 Cambridge Science Park, Milton Road,
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ADP number *(if known)* 7514136002

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❺ Claiming an arlier application date

5 Are you claiming that this application be treated as having been filed on the date of filing of an earlier application?

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Yes ☐ No X ☐ → ***go to 6***

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15(4) (Divisional) ☐ 8(3) ☐ 12(6) ☐ 37(4) ☐

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❻ If you are declaring priority from a PCT Application please enter 'PCT' as the country and enter the country code (for example, GB) as part of the application number.

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7 Are you (the applicant or applicants) the sole inventor or the joint inventors?

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Yes ☐ No ☒ ➡ ***A Statement of Inventorship on Patents Form 7/77 will need to be filed (see Rule 15).***

❽ Please supply duplicates of claim(s), abstract, description and drawing(s).

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8a Please fill in the number of sheets for each of the following types of document contained in this application.

		Continuation sheets for this Patents Form 1/77	—
Claim(s)	4	Description	13 8M
Abstract	1	Drawing(s) (FORMAL)	7+7

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8b Which of the following documents also accompanies the application?

Priority documents *(please state how many)*	—
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Patents Form 7/77 – Statement of Inventorship and Right to Grant *(please state how many)*	1.
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A Photon Source

The present invention relates to a photon source. More specifically, the present invention relates to a photon source with a fast photon emission rate, or a single photon emitter.

The photon source of the present invention is a so-called 'low-dimensional structure'. Typically, these are fabricated from semiconductor materials. In such a low-dimensional structure, the energy of the carriers is confined in one or more dimensions so that the carriers may only occupy a single or a plurality of discrete energy levels in the direction of confinement. In a two dimensional carrier gas, the carriers are free to move in two dimensions but they are restricted to move in one or more discreet energy levels in the third dimension. Similarly, in a zero dimensional structure a so called 'quantum dot', the carriers may only occupy one energy level (in a true zero dimensional structure) or a plurality of discreet energy levels in a quasi zero dimensional structure.

A photon source can emit photons due to the radiative recombination of electrons and holes. Electrons and holes can non-radiatively recombine or, may undergo other interactions which prevent the emission of photons. The present invention seeks to address this problem and provides a photon source with an enhanced radiative recombination. Also, the present invention can be extended to a single-photon source which emits a stream of single photons. Such single-photon sources are now becoming of interest for the emerging fields of quantum cryptography and quantum computations.

In a first aspect, the present invention provides a photon source comprising:

an active layer having a low dimensional carrier gas with an excess of carriers of a first type; and

tuning and injection means for varying the excess carrier concentration of carriers of the first type in the active layer and for injecting a carrier of a second type into the active layer such that radiative recombination can occur between the carrier of the second type and a carrier of the first type, wherein carriers of the second type have the opposite polarity to those of the first type.

The applicants have surprisingly found that the photon emission rate for minority carriers injected into a quantum well which supports an excess population of electrons is fast compared to the case where both carrier types are injected in small concentrations into a quantum well. In this latter case, the recombination is excitonic and is governed by the relevant energy-momentum conservation rules resulting in a decay time of about nanoseconds. In of recombination of a minority carrier in a low dimensional carrier gas, excess carriers may be involved in the recombination process which relax the energy momentum conservation rules.

The efficiency of a light source is, to a large extent, governed by the relative rates of radiative and non-radiative recombination. A faster radiative recombination rate results in a higher efficiency given the same non-radiative recombination rate.

The source will be described with electrons as carriers of the first type and holes as carriers of the second type. Although, it will be appreciated that the carriers of the first type may be holes and the carriers of the second type may be electrons.

In a low dimensional structure a single or a plurality of discrete energy levels will be defined in the conduction band of a quantised system such as a 2D, 1D or 0D low dimensional gas. These conduction band levels are capable of being populated by electrons. Similarly valence band states or level are set up in the valence band and such states are only capable of being populated by holes.

The carriers of the second type need to be injected into the active layer, this may be achieved by resonant tunnelling. If the structure is configured to allow resonant

tunnelling, then it will be possible to configure the source to allow injection of carriers into the active layer under predetermined operating conditions.

The second type carrier or carriers can resonantly tunnel into the active layer when a valence band energy level in the active layer aligns with the energy of the injected carriers.

Therefore, preferably, the active layer will have a confined energy level capable of being populated with a carrier of a second type and the tuning and injecting means can be configured to inject second type carriers at the energy of the confined energy level.

Preferably, the source will further comprise a tunnel layer. This layer will be located such that a carrier or carriers of the second type will tunnel from this layer into the active layer. The tunnel layer will preferably be capable of supporting a low dimensional carrier gas having a confined energy state which is capable of being populated with a carrier of the second type, said tuning and injection means being capable of aligning the confined energy state of the tunnel layer with the confined energy state of the active layer. Although the tunnel layer will be capable of supporting a low dimensional carrier gas, the tunnel layer will usually not hold any excess carriers, unless these carriers are about to tunnel into the active layer.

The tunnel layer can act as a valve which can only allow the passage of holes if a valence band level in the tunnel layer aligns with that of the valence band level in the active layer.

By injecting minority carriers one-by-one into the active layer, a single photon source can be realised. The addition of one minority carrier resulting in the emission of a single photon. If the radiative recombination rate is enhanced the uncertainty or 'jitter' in the time of photon emission is reduced. The reduction of 'jitter' is important in, for example, quantum cryptography. This is because the detector to which the single photon is sent is usually gated so as to be sensitive for only a short period of time

corresponding to the expected arrival time of the photon. A large jitter means that the detector must be sensitive for a long time which results in a higher backgrounds noise and lower photon detection efficiency.

Also, the efficiency of the source is increased as described for the multiple photon source.

The present invention may be configured as a single photon source. For such a source, it is required to introduce carriers of the second type (in this description holes) into the active layer one by one. This is possible if the tunnelling layer comprises a quantum dot. The aligned valence band layer of the quantum dot can only accommodate a single hole at a time. Therefore, it is possible to introduce holes one by one into the active layer by varying the tuning means to align a valence band level in the tunnel layer with a valence band layer in the active layer.

More explicitly this can be achieved because under a certain bias condition (which can easily be determined for the particular source though experiment) an energy level of the quantum dot becomes resonant with the hole reservoir region. When a hole tunnels into the quantum dot increased coulomb repulsive interaction between the holes prohibits subsequent hole tunnelling into the same dot. In this way, the quantum dot is filled with only one minority carrier. The bias is further increased to bring this filled quantum dot hole state into resonance with a confined valence band state in the quantum well. The hole may then tunnel into the active layer.

However, in order for the hole to be in the tunnel layer ready to tunnel into the active layer, the hole must usually tunnel into the tunnel layer. Typically, it will be possible to operate the injection and tuning means, such that only a valence band level in the tunnel means aligns with the carrier energy of the carriers entering the tunnel layer to allow a single hole to tunnel into the tunnel layer. (In other words, tunnelling of holes into the active layer will be blocked).

Then, the injection and tuning means will be configured to align a valence band level of the tunnel layer with that of a valence band level of the active layer. Thus, the hole can tunnel from the tunnel layer into the active layer where it can recombine with an electron.

Using the above operation, it will be possible to control the flow of holes into the active layer with the tuning means such that the holes can be introduced one-by-one into the active region for recombination.

The idea of using the injection and tuning means to switch between two states where the first state allows tunnelling into the tunnel layer and the second state allows tunnelling from the tunnel layer to the active layer, can also be used when the tunnel layer can hold more than a single hole. For example, when the tunnel layer has just two dimensional confinement.

The tuning and injection means have been introduced together. However, they perform two distinct functions: a 'tuning function' to vary the carrier concentration of the active layer to maximise the radiative recombination rate and an 'injection function' to inject carriers into the active layer. These functions may be performed by two separate components for example, two gates where one gate varies the carrier concentration and the other varies, for example, the band structure to allow or prohibit resonant tunnelling. However, they could both be performed to a certain extent by a single component. Alternatively, a plurality of components could be used to effect both functions, but where a component did not exclusively affect either the tuning or the injection.

The tuning and injection means may be provided by electrodes, for example, a gate type electrode where a voltage applied to the gate affects transport within a remote layer or heavily doped layers which may be used to apply a DC bias across the device. Gates may be provided on one or both sides of the active layer, tunnel layer and the reservoir region. These gates may be embedded gates or surface gates.

Typically, ohmic contacts may be provided to the active layer and a gate may be provided such that variation of the gate bias with respect to the ohmic contacts serves to vary the carrier concentration in the carrier gas in the active quantum well.

Preferably, a second gate is provided in addition to the first gate. The second gate will generally be located on an opposing side of the active layer to the first gate. The provision of two gates allows finer control over the source. Thus, it is possible for there to be a range of different excess carrier concentrations for a particular injection condition of a second type carrier. An injection condition being a particular alignment of energy levels for resonant tunnelling or a particular injection energy if resonant tunnelling is not used to introduce carriers into the active layer.

The first gate will primarily control the excess carrier concentration in the active layer (or 'tune' the source) and the second gate will primarily control the band structure to align the levels for resonant tunnelling (or control the injection). However, in some device configurations the two gates may affect both tuning and injection and the bias applied to both gates will need to be changed in order to vary the carrier concentration for a particular injection condition.

Typically, the source will further comprise a reservoir region which will comprise excess carriers of the second type.

Preferably, a first barrier is provided so that minority carriers tunnel through this barrier before entering the active layer. If a tunnel layer is present, this barrier layer will be provided between the tunnel layer and the active layer. More preferably, a second barrier is provided before the carriers enter the tunnel layer. If a reservoir region is provided this layer will preferably be located between the reservoir region and the tunnel layer. The barriers may be a single layer or they may be a plurality of layers. A barrier layer will have a larger bang-gap than those of the layers which it separates. For example, the first barrier will have a larger band-gap than the active layer and the tunnel

layer. The second barrier layer will have a larger band-gap than the tunnel layer and the reservoir region.

A third doped barrier layer is also preferably provided to provide excess carriers to the active layer. The third barrier layer may be a modulation doped barrier layer comprises a doped barrier layer and an undoped spacer layer adjacent the active layer.

Generally, carriers of the second type will be injected generally perpendicular to the active layer. The term generally perpendicular should be understood as meaning that the second type carriers are not injected in the plane of the active layer but are instead injected from a layer which is formed above or below the active layer during growth of the structure. Of course, the second type carriers could be injected within the plane of the active layer.

In a second aspect the present invention provides a method of operating a photon source, the photon source comprising:

an active layer having a low dimensional carrier gas with an excess of carriers of a first type; the method comprising the steps of:

varying the excess carrier concentration to maximise the radiative recombination rate and injecting a carrier of a second type into the active layer for radiative recombination with a carrier of the first type; wherein carriers of the second type have the opposite polarity to those of the first type.

More preferably, step of varying the excess carrier concentration will comprise the step of maximising the excess carrier concentration of the active layer.

Even more preferably, the step of varying the excess carrier concentration will comprise the step of biasing a gate with respect to said active layer.

The step of injecting a carrier of the second type will preferably comprise the step of applying a bias to a gate to affect the band structure of the source to allow resonant tunnelling of a second type carrier into the active layer.

The present invention will now be described with reference to the following non-limiting preferred embodiments in which:

Figure 1 shows a band structure of an optical source in accordance with the present invention;

Figure 2 shows a variation in the band structure of Figure 1;

Figure 3 shows a semiconductor device in accordance with an embodiment of the present invention;

Figure 4 shows a band structure of a single photon source in accordance with an embodiment of the present invention;

Figure 5 shows a schematic band structure of a single photon source in accordance with an embodiment of the present invention;

Figure 6 shows a semiconductor device in accordance with an embodiment of the present invention; and

Figure 7 shows a plot showing radiative recombination as a function of excess carrier concentration.

The preferred embodiments of the invention will be described with electrons as the first type carriers and holes as the second type carriers. However, it will be appreciated by

those skilled in the art that the inverse devices could be envisaged with holes as the first type carriers and electrons as the second type carriers.

Figure 1 shows a schematic band structure of a photon source in accordance with an embodiment of the present invention. A conduction band 1 and a valence band 3 are shown. The conduction band 1 defines the rules for the conduction of electrons through the layers of the device and the valence band 3 defines the transport characteristics of the holes in the device.

The band structure of the device will initially be described with respect to the conduction band 1. In the conduction band 1, a quantum well is a minima in the conduction band where electrons may be trapped. The device comprises an active layer 5 which is a quantum well layer. This layer 5 is capable of supporting a two dimensional electron gas 7. The active layer 5 is separated from tunnel layer 9 by a first barrier layer 11. Tunnel layer 9 is again a quantum well layer.

A plurality of confined energy levels may be formed in tunnel layer 9. However, tunnel layer 9 does not have excess carriers. First barrier layer 11 interposed between tunnel layer 9 and active layer 5 prevents tunnelling between tunnel layer 9 and active layer 5 unless a confined energy level of tunnel layer 9 and active layer 5 are aligned. The first barrier layer 11 has a larger band gap than both the active layer 5 and the tunnel layer 9. To confine the carrier states in tunnel layer 9, a second barrier layer 13 is provided. Second barrier layer 13 is disposed between tunnel layer 9 and a reservoir region of holes 15. Reservoir region of holes may be provided by a p-doped layer. The inverse structure is seen in the valence band 3. However, here, a quantum well for holes is defined by a maximum in the valence band. A front gate 17 which is a Schottky gate is provided on the side of the structure parallel to and closest to the active layer 5. A back gate 19 is provided on the opposing side of the structure.

Ohmic contacts (not shown) are provided to the active layer 5 such that the front 17 or back 19 gates may be biased with respect to the active layer 5.

Applying a bias via the front gate 17 to the active layer 5 serves to vary the carrier concentration of the 2DEG 7 within active layer 5. Applying a bias to the back gate 19 serves to vary the band structure as shown in Figure 2.

For clarity, where possible, the same reference numerals have been used in Figure 2 as in Figure 1. The front 17 and back 19 gates have been omitted from Figure 2. In Figure 2, a confined conduction band state 21 and a confined valence band state 23 are shown in the active layer 5. Further, a confined valence band state 25 and a confined conduction band state 27 are shown in the tunnel layer 9. Under the operating conditions shown in Figure 2, tunnelling is inhibited and holes accumulate in the structure as shown in the figure in the region 15. Only suitable bias is applied so that the confined valence band state 23 with the first active layer 25 aligns with a confined valence band state 25 of the tunnel layer 9, holes tunnel into the tunnel layer 25 and then into the active layer 5. Electron tunnelling is not allowed as the confined electron level 27 of the tunnel layer 9 is not aligned with the confined conduction band level 21 of the active layer 5. Once the bias is changed so that valence band levels 23 and 25 do not align, tunnelling of holes is inhibited. Thus, tunnel layer 9 acts as a valve which can be switched on (valence band levels 23 and 25 align) to allow injection of holes into the active layer 5 or switched off (valence band levels 23 and 25 do not align).

The use of both the front gate and back gate allow the carrier concentration of the electrons in the active layer 5 to be maximised for a given alignment of valence bands. The increase carrier concentration in the active layer increases the chances of a hole radiatively recombining with an electron in the active layer 5. This enhances the possibility of photon emission.

Figure 3 shows a possible layer structure which can be used to create the schematic band structure of Figures 1 and 2.

A p-doped GaAs layer is formed on a substrate. The layer 31 is Be doped with a carrier concentration of $10^{18}cm^{-3}$. The layer is grown to 200nm An 80nm layer 33 is formed on an upper surface of the p-doped layer 31. The p-doped layer 31 will serve as a reservoir region for holes. A second tunnel barrier layer 35 is then formed overlying an upper surface of the undoped layer 33. The second barrier layer 35 is undoped AlGaAs. A tunnel layer 37 of 29nm GaAs is then formed overlying the second barrier layer 35. A first barrier layer 39 of AlGaAs 10nm is formed overlying an upper surface of the tunnel layer 37. An active layer 41 is then formed overlying an upper surface of the first barrier layer 39. The active layer is formed from 30nm GaAs. A 60nm undoped spacer layer of AlGaAs 43 is then formed overlying an upper surface of the active layer 41. A doped barrier layer 45 which serves to provide electrons to the active layer 41 is formed from 200nm of Si doped ($10^{17}cm^{-3}$) of AlGaAs. This is so-called remote doping of the active layer reduces impurity scattering and increases the mobility of the two dimensional carrier gas, resulting in a device of high quality. The semiconductor layers of the structure are finished with a GaAs cap layer of 17nm 47 which is formed overlying an upper surface of the doped barrier layer 45. Ohmic contacts 49 and 51 are then formed to contact the active layer 41. The ohmic contacts are formed from AuGeNi. They are annealed so to defuse down into the active layer 41. A back gate of AuGeNi is formed on the lower surface of p-doped layer 31. A front gate of semi-transparent NiCr (8nm) is formed overlying an upper surface of the GaAs cap layer 47.

Figure 4 shows a variation on the band structure of Figure 1. Where possible, the same reference numerals have been used. The structure is very similar to that described with reference to Figure 1. However, the tunnel layer 9 is instead formed from a plurality of quantum dots. The operation of this device is described with reference to Figure 5. For clarity, only a single quantum dot will be described. As this device is to be configured as a single photon source, it is important that only one hole is introduced into the active layer 5 at a time. Again, for clarity, the same reference numerals have been used where possible.

In Figure 5A, a plurality of valence band levels 61 and 63 are formed in the dot tunnel layer 9. The back gate bias is varied so that the confined valence band level 61 aligns with that of the hole reservoir 15. Thus, a hole tunnels from the reservoir 15 into confined valence band levels 61. Only one hole can tunnel at a time. This is because coulomb repulsion prevents the tunnelling of a subsequent hole into the same dot. Also, as the energy level 61 is not aligned with valence band energy level 23, then a hole cannot tunnel from valence band level 61 into the active layer 5.

The bias is then further changed as shown in Figure 5B so that valence band layer 23 aligns with valence band layer 61. Therefore, a hole can tunnel from the tunnel layer 9 into the active layer 5 and radiatively recombine to emit a photon.

Figure 6 shows a possible layer structure of the single photon device. Many of the layers are identical to those described in relation to Figure 3. Therefore, to avoid repetition, the same numerals have been used where appropriate.

The region of the device known as the tunnelling region 71 differs from that shown in Figure 3. As in Figure 3, a first undoped AlGaAs tunnel layer is formed. This is layer 35. Two mono layers of InAs are then formed overlying an upper surface of the second tunnel layer. These layers formed quantum dots using the well known Stranskii-Krastanov process. A 10nm layer of AlGaAs first barrier layer is then formed overlying the dot layer 73. The remainder of the process remains identical.

For a photon emitter, be it a single photon emitter or a more conventional multiple photon source, the efficiency is covered by the relative rates of radiative and non radiative recombination. Hence, the efficiency of the device is maximised by increasing the radiative recombination rate. For a single photon emitter, the time during which emission takes place must be as rapid as possible. This is also to minimise jitter, the uncertainty in the time of emission of a photon. Also, for a single photon emitter operating by the radiative recombination of a single charged carrier, the efficiency of the

radiative process must be high. Both of these requirements call for as rapid a decay rate as possible.

In order to verify this principle, Figure 7 shows results of the radiative decay time of the quantum well emission as a function of front gate bias. The front gate bias can be equated to the excess carrier density. The bias is where the quantum well is depleted of electrons (about -0.8 volts), a decay time of 650 ps is observed. As a bias is made more positive, the decay time reduces dramatically to a minimum of 110 ps at -0.6 volts, it can be seen that as the excess electron density is increased further, the decay time rises. It is therefore advantageous to have an active region which has a tuneable excess electron density so as to be able to ensure a minimum in the radiative decay time.

CLAIMS:

1. A photon source comprising:

an active layer having a low dimensional carrier gas with an excess of carriers of a first type; and

tuning and injection means for varying the excess carrier concentration of carriers of the first type in the active layer and for injecting a carrier of a second type into the active layer such that radiative recombination can occur between the carrier of the second type and a carrier of the first type, wherein carriers of the second type have the opposite polarity to those of the first type.

2. A photon source according to claim 1, wherein said active layer has a confined energy level capable of being populated with a carrier of a second type, and said injection and tuning means is capable of injecting a second type carrier at the energy of the confined energy level.

3. A photon source according to claim 2, further comprising a tunnel layer said tunnel layer being capable of supporting a low dimensional carrier gas having a confined energy state which is capable of being populated with a carrier of the second type, said tuning and injection means being capable of aligning the confined energy state of the tunnel layer with the confined energy state of the active layer.

4. A photon source according to claim 3, wherein the tunnel layer comprises at least one quantum dot capable of confining a single carrier of the second conductivity in the confined energy state of the tunnel layer.

5. A photon source according to any preceding claim, wherein the tuning and injection means are capable of varying the carrier concentration of excess carriers for a particular injection condition of a second type carrier.

6. A photon source according to claim 5, when dependent on either of claims 3 or 4, wherein the tuning and injection means are configured to vary the excess carrier concentration of the active layer for a particular alignment of the said energy levels of the active and tunnel layer.

7. A photon source according to any preceding claim, wherein said tuning and injection means comprise an ohmic contact provided to the active layer and a first gate provided to control the carrier concentration of said first carrier type in said active layer.

8. A photon source according to claim 7, wherein the tuning and injection means comprises a second gate located on an opposing side of the active layer to the first gate.

9. A photon source according to any preceding claim, wherein a first barrier layer is provided such that a second type carrier tunnels through the first barrier layer before it enters the active layer.

10. A photon source according to any of claims 3 or 4 to 9 when dependent on claim 3, wherein a second barrier layer is located such that such that a second type carrier tunnels through the second barrier layer before it enters the tunnel layer.

11. A photon source according to any preceding claim, wherein the source further comprises a reservoir region comprising an excess of second type carriers.

12 A photon source according to claim 11 when dependent on claim 3, wherein the tuning and injection means are configured to align the confined energy state of the tunnel layer with that of the energy of carriers of the second type in the reservoir.

13. A photon source according to any preceding claim, wherein the tuning and injection means are configured to switch the source between a first tunnel state where the confined energy level of the tunnel layer is only aligned with the energy of second

type carriers in the reservoir and a second state where the confined energy level of the tunnel layer is only aligned with the confined energy level of the active layer.

14. A photon source according to any preceding claim, wherein the carriers of the first type are electrons and the carriers of the second type are holes.

15. A photon source according to any preceding claim, wherein a carrier of the second type is injected generally perpendicular to the active layer.

16. A photon source according to any of claims 1 to 14, wherein a carrier of the second type is injected generally parallel to the active layer.

17. A method of operating a photon source, the photon source comprising:

an active layer having a low dimensional carrier gas with an excess of carriers of a first type; the method comprising the steps of:

varying the excess carrier concentration to maximise the radiative recombination rate and injecting a carrier of a second type into the active layer for radiative recombination with a carrier of the first type; wherein carriers of the second type have the opposite polarity to those of the first type.

18. A method of operating a photon source according to claim 17, wherein the step of varying the excess carrier concentration comprises the step of maximising the excess carrier concentration of the active layer.

19. A method of operating a photon source according to either of claims 17 or 18, wherein the step of varying the excess carrier concentration comprises the step of biasing a gate with respect to said active layer.

20. A photon source as substantially hereinbefore described with reference to any of the accompanying drawings.

21. A method of operating a photon source as substantially herein before described with reference to any of the accompanying drawings.

A Photon Source

ABSTRACT:

A photon source comprising:

an active layer (5) having a low dimensional carrier gas with an excess of carriers of a first type; and

tuning and injection means (17, 19) for varying the excess carrier concentration of carriers of the first type in the active layer (17) and for injecting a carrier of a second type into the active layer such that radiative recombination can occur between the carrier of the second type and a carrier of the first type, wherein carriers of the second type have the opposite polarity to those of the first type.

The source may be configured as a single photon source.

Figure 1

Figure 1

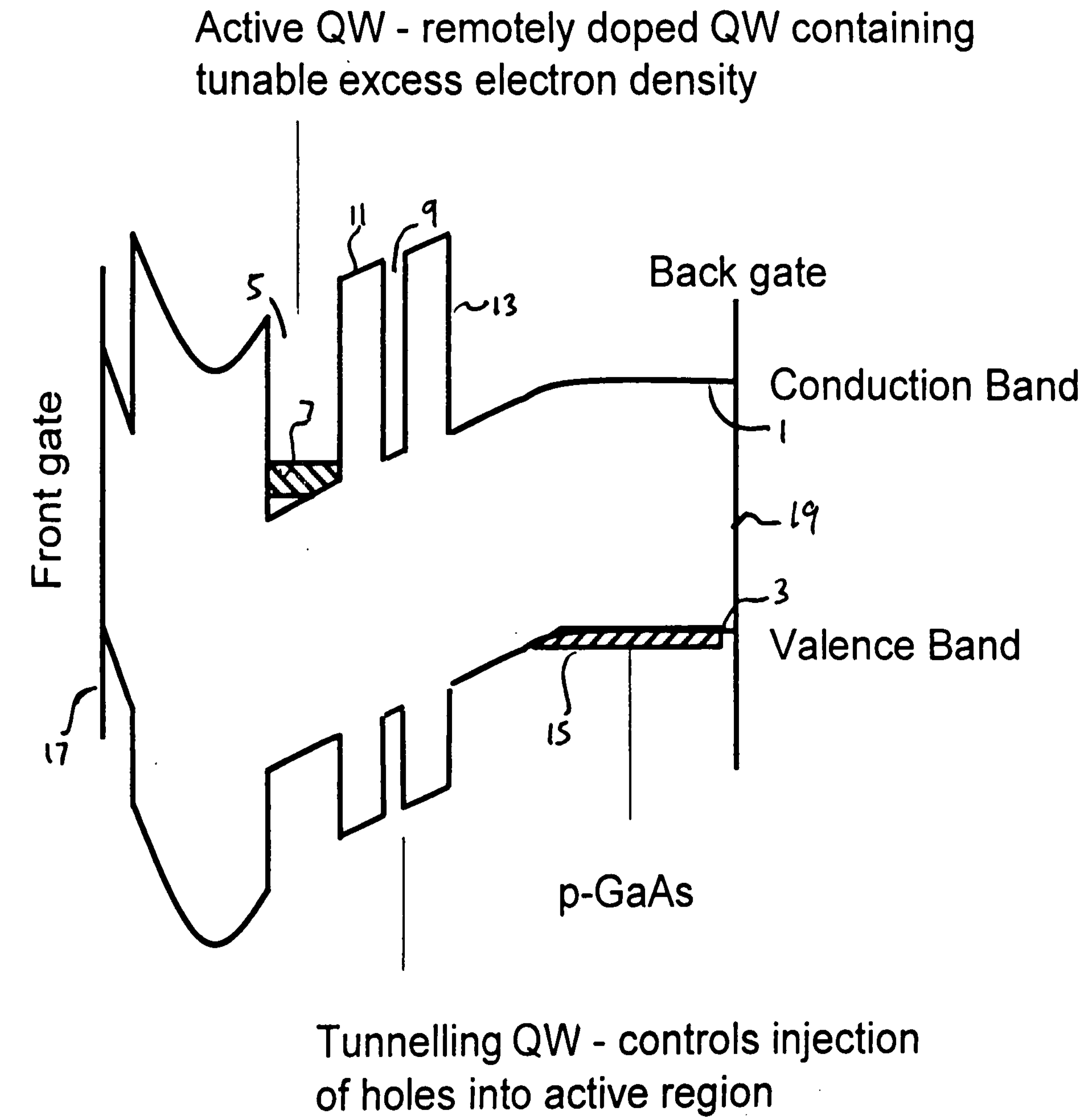

Active QW - remotely doped QW containing
tunable excess electron density
Front gate
Back gate
Conduction Band
Valence Band
p-GaAs
Tunnelling QW - controls injection
of holes into active region
1
3
5
7
9
11
13
15
17
19

Figure 2

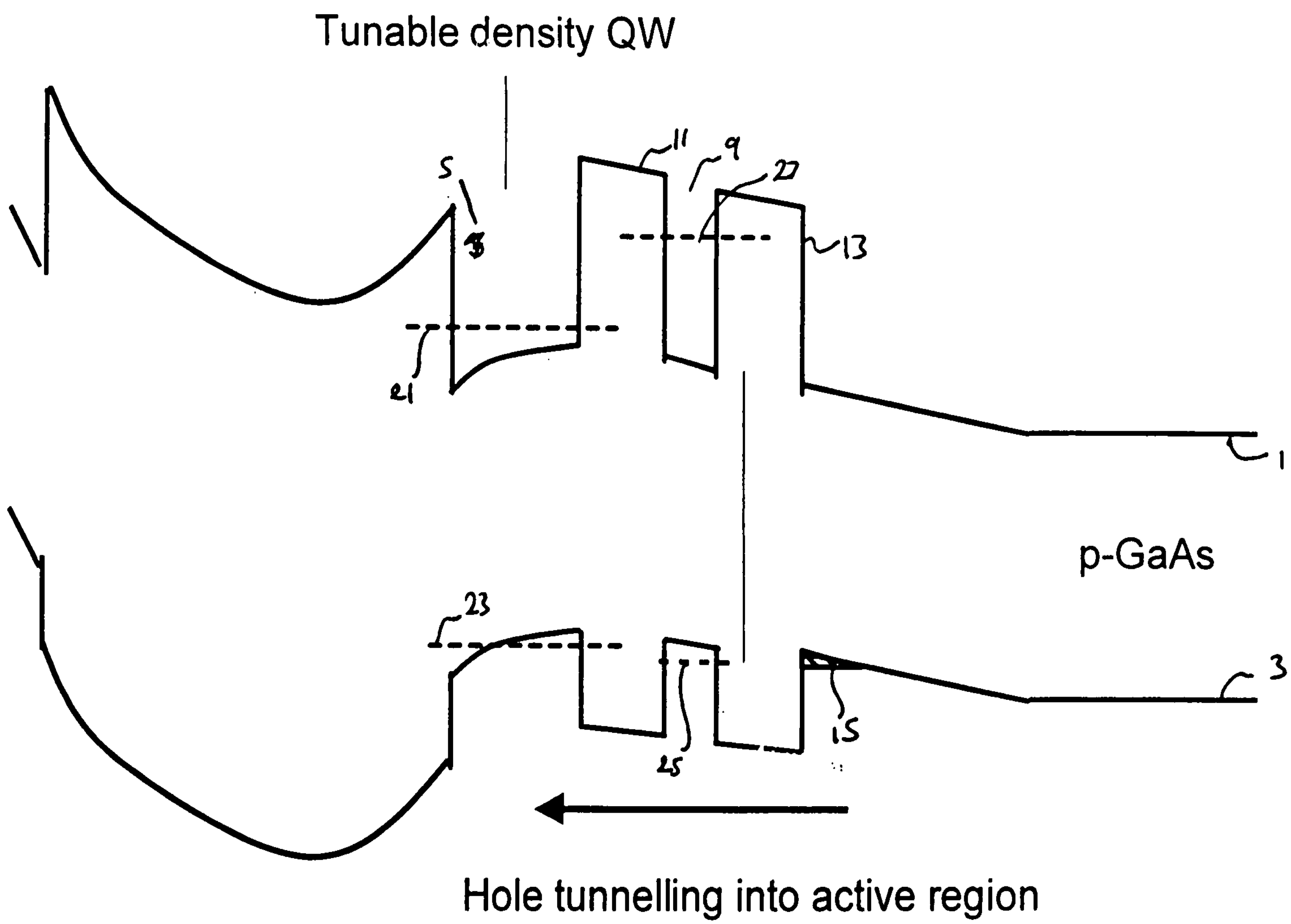

Tunable density QW
5
3
11
9
22
13
21
1
p-GaAs
23
25
15
3
Hole tunnelling into active region

Figure 3

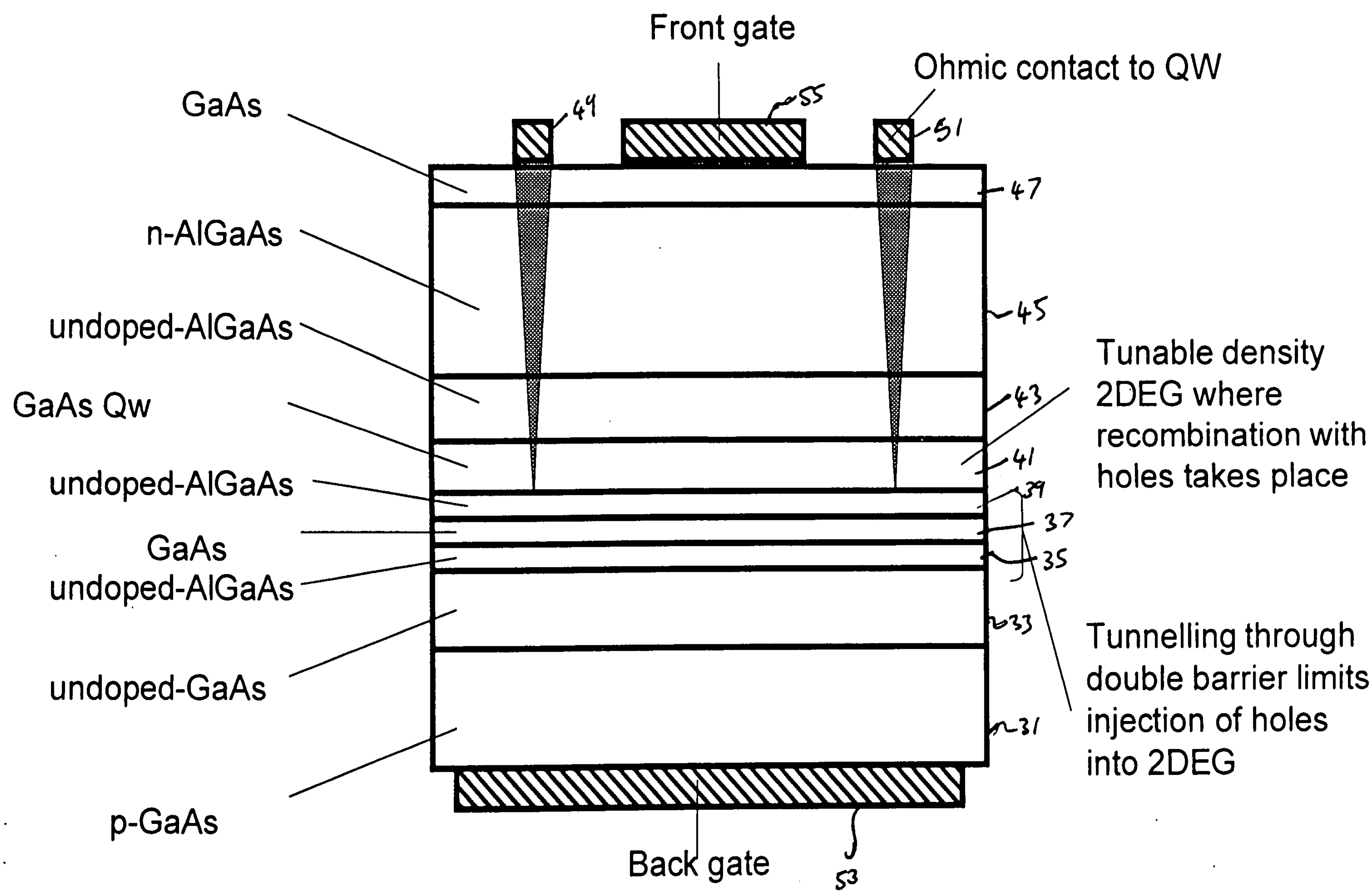

Front gate
Ohmic contact to QW
GaAs
n-AlGaAs
undoped-AlGaAs
GaAs Qw
undoped-AlGaAs
GaAs
undoped-AlGaAs
undoped-GaAs
p-GaAs
Back gate
Tunable density 2DEG where recombination with holes takes place
Tunnelling through double barrier limits injection of holes into 2DEG
55
49
51
47
45
43
41
39
37
35
33
31
53

Figure 4

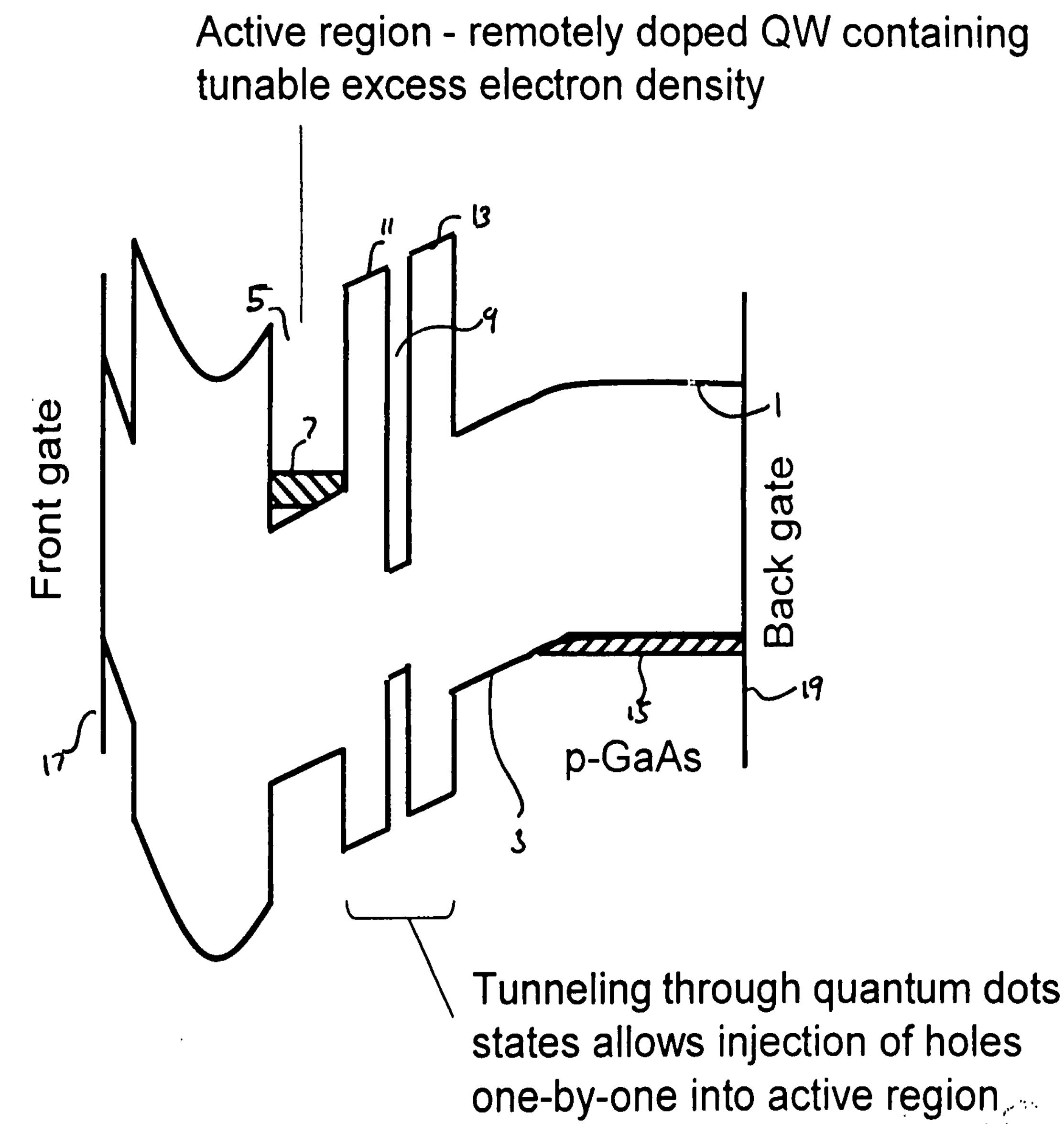

Active region - remotely doped QW containing tunable excess electron density
Front gate
Back gate
p-GaAs
Tunneling through quantum dots states allows injection of holes one-by-one into active region
1
3
5
7
9
11
13
15
17
19

Figure 5

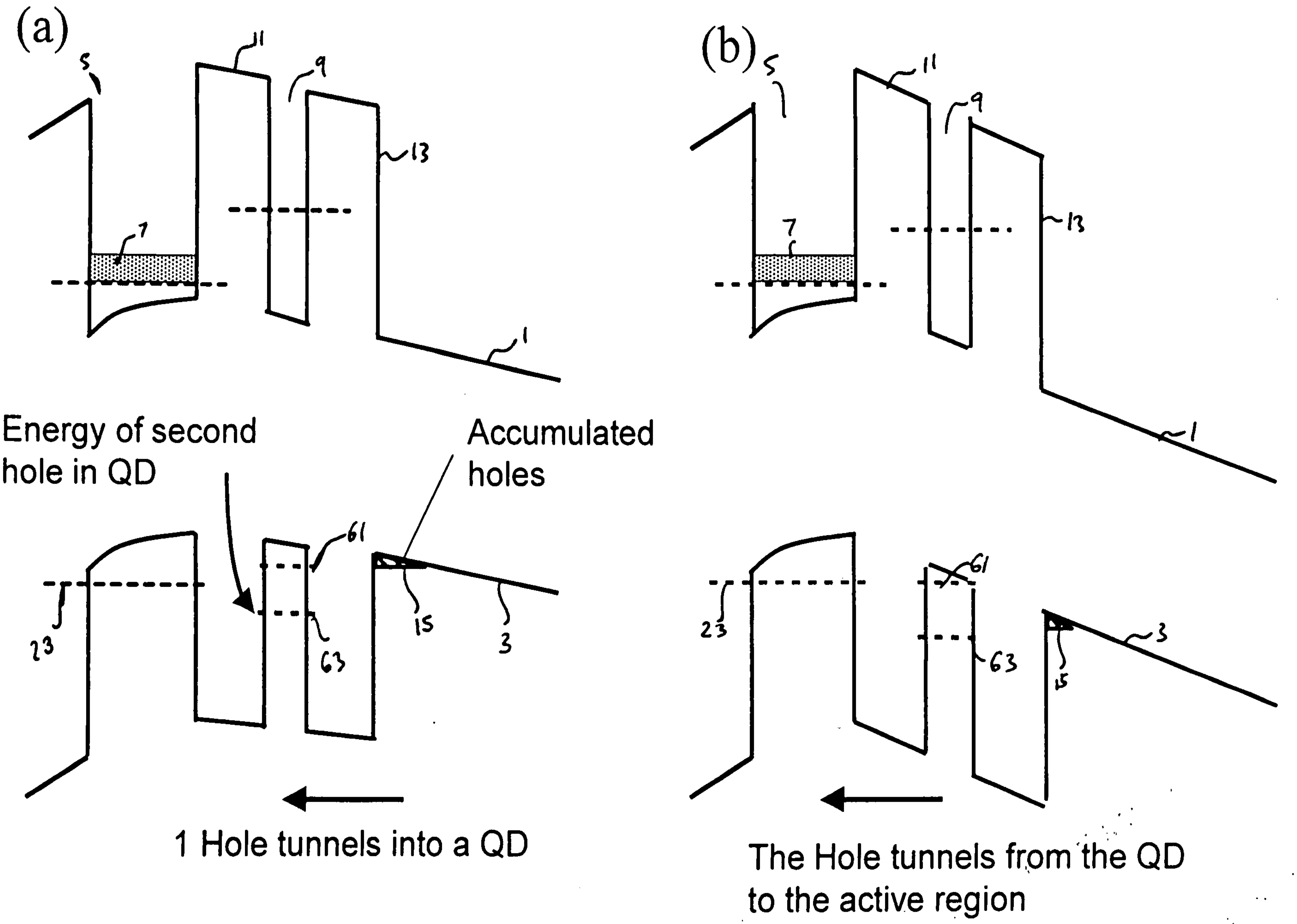

(a)
5
11
9
13
7
1
Energy of second hole in QD
Accumulated holes
61
23
63
15
3
1 Hole tunnels into a QD
(b)
5
11
9
13
7
1
61
23
63
15
3
The Hole tunnels from the QD to the active region

Figure 6

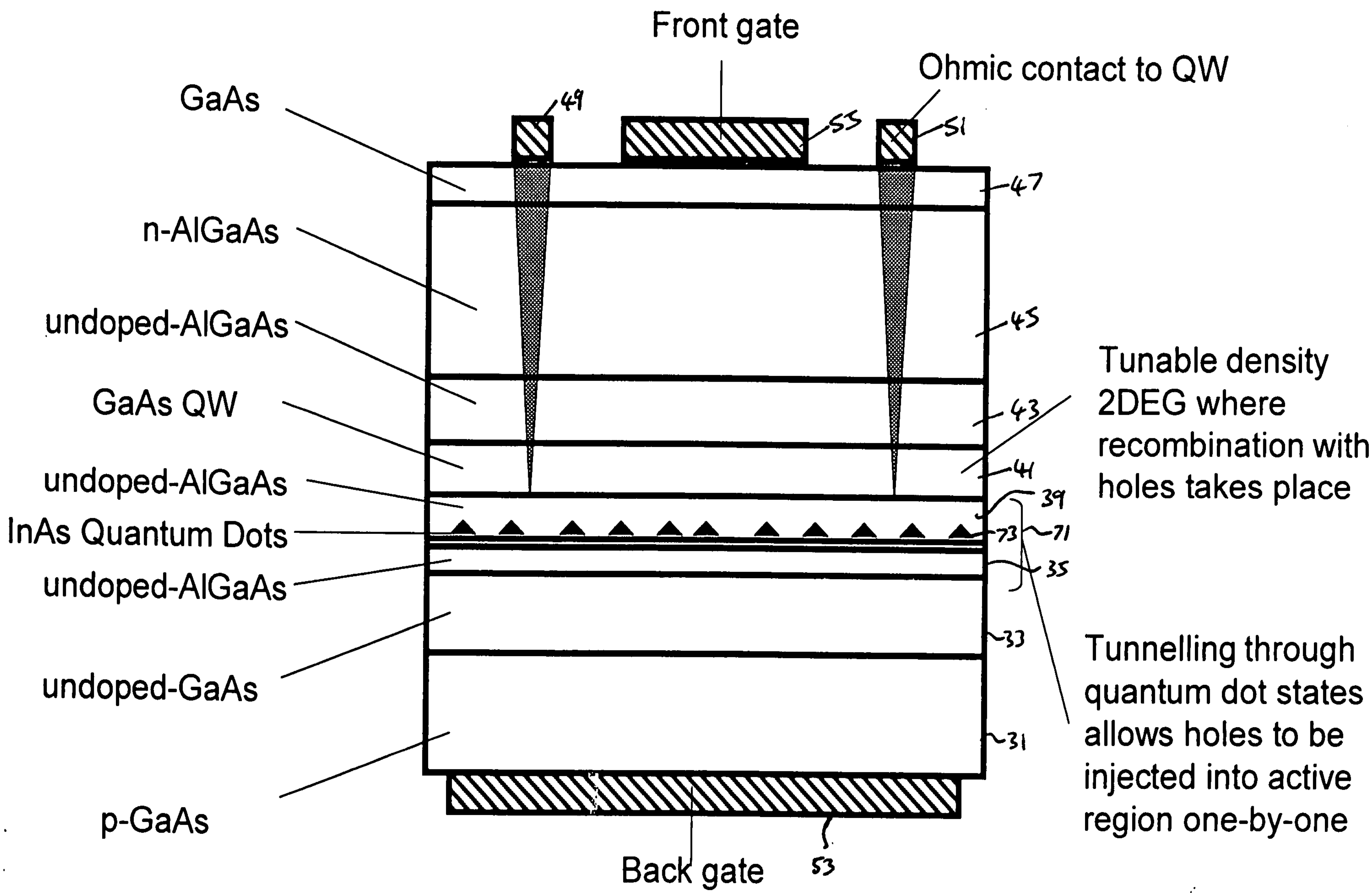
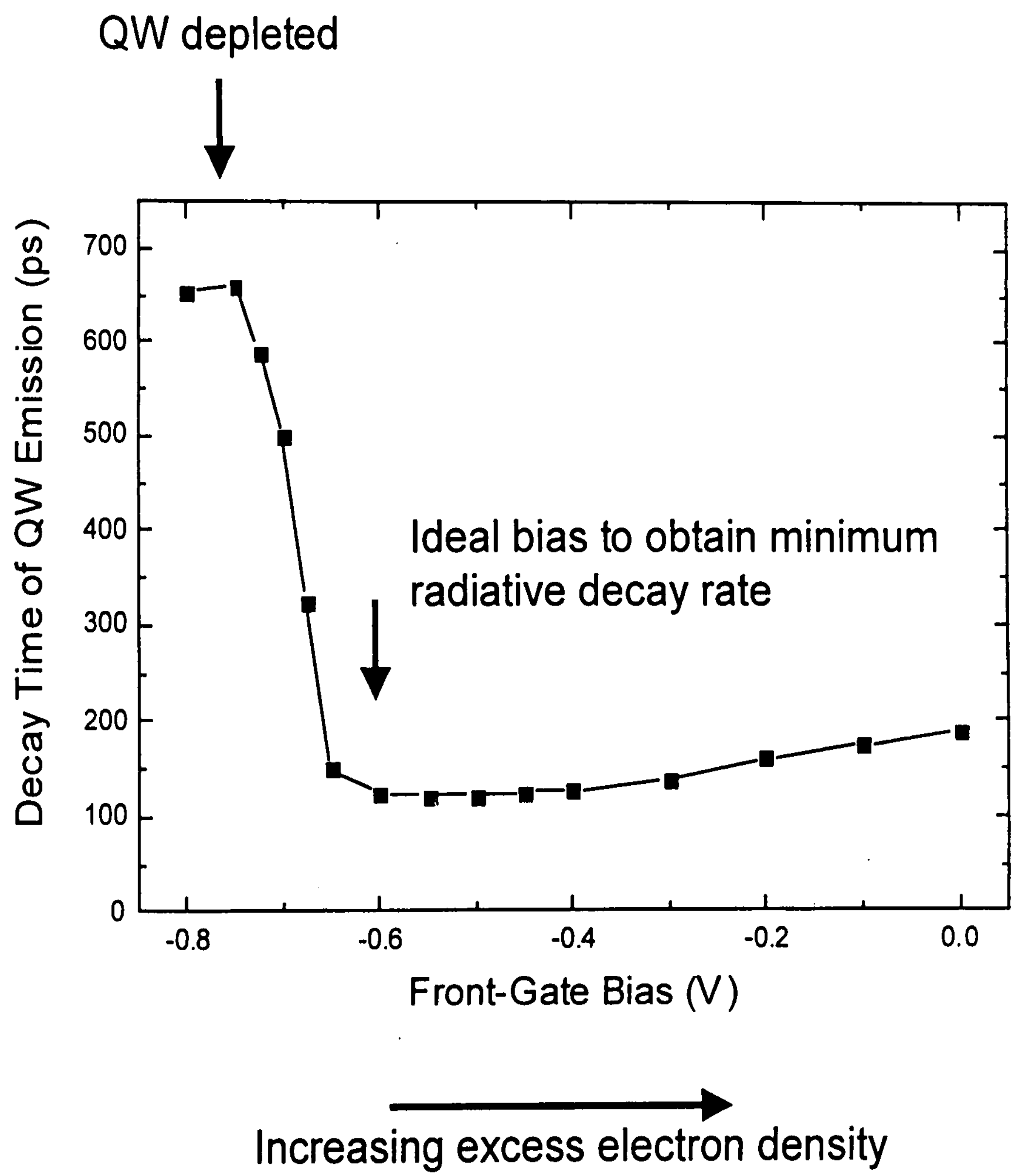

Front gate
Ohmic contact to QW
GaAs
n-AlGaAs
undoped-AlGaAs
GaAs QW
undoped-AlGaAs
InAs Quantum Dots
undoped-AlGaAs
undoped-GaAs
p-GaAs
Back gate
Tunable density 2DEG where recombination with holes takes place
Tunnelling through quantum dot states allows holes to be injected into active region one-by-one
49
55
51
47
45
43
41
39
73
71
35
33
31
53

Figure 7


QW depleted
Ideal bias to obtain minimum
radiative decay rate
Decay Time of QW Emission (ps)
0
100
200
300
400
500
600
700
-0.8
-0.6
-0.4
-0.2
0.0
Front-Gate Bias (V)
Increasing excess electron density